EARTH'S ICE SHEETS AND ICE SHELVES AS AN ANALOG FOR EUROPA'S ICY SHELL. D. D. Blankenship[1] and D. L. Morse[1], [1]Institute for Geophysics, John A. and Katherine G. Jackson School of Geosciences, The University of Texas at Austin, 4412 Spicewood Springs Rd, Bldg 600, Austin, TX, 78759 (blank@ig.utexas.edu).

Introduction: Earth's ice sheets and ice shelves could be viewed as poor analogs for understanding physical states and the processes governing these states within Europa's icy shell because their formation is dominated by atmospheric processes. However below the top few tens of meters, the atmosphere ceases to dominate their physical state so they become increasingly relevant as analogs for Europa. Our intent is to examine the thermal, structural and compositional states of Earth's ice sheets and ice shelves from the perspective of their governing processes, then to relate these processes to those hypothesized for Europa. Our ultimate goal is to elucidate possible observable physical states within Europa's icy shell based on these analogous processes.

Thermal State: Earth's polar ice sheets in East Antarctica, West Antarctica and Greenland are up to five km in thickness and have surface temperatures ranging from 213 – 273 K. In many cases, their internal temperature profiles are nearly isothermal in the upper half, where vertical advection of cold material from above (snow) dominates, and linearly increasing with depth in the lower half where upward conduction of geothermal and latent heat dominates. Strain heating, horizontal advection and spatially- or temporally-varying boundary conditions all contribute to deviations from this simplified description. A significant deviation from this temperature structure exists for polythermal ice caps (e.g., Svalbard) where significant thicknesses of temperate ice (isothermal at the pressure melting point) are found at the base, overlain by a linearly-varying layer. These profiles generally result from the vertical advection of heat by surface melt draining through the colder upper layer of these ice caps. The temperature profiles for ice shelves are widely varied as the profile inherited from the present ice sheet continues to be modified by downward advection of accumulating material and melt/freeze processes become dominant at the base. Advected heat either from surface melt or ocean infiltration can substantially modify these profiles.

Many processes analogous to those responsible for the thermal state of Earth's ice sheets and ice shelves have been proposed for Europa's icy shell. These include an overlying kilometers-thick brittle shell where thermal conduction is thought to dominate but with added tidally driven strain heating or possibly substantial melting and freezing at depth. In addition, the vertical advection of heat by the redistribution of surface material by sputtering (frost) and gardening, downslope motion or the draining of brines may be thermally analogous. Finally, it should be noted that there are no known Earth analogs for thermal convection within a deep ductile layer that has been proposed for Europa although the thermal processes in Earth's polythermal glaciers may yet prove analogous if tidally driven heating is distributed throughout Europa's icy shell.

Structural State: Here we characterize the structural state of Earth's ice sheets and ice shelves considering the density variations and the distribution of fracture associated with ice streams, which are fast-flowing regions within Earth's ice sheets that are many tens of kilometers in width and hundreds of kilometers in length. Ice streams are also the dominant contributor to ice shelf volume.

Density layering in the upper few tens of meters of Earth's ice sheets and ice shelves is pervasive. This is because ice sheet surfaces on Earth are continually generated by deposition and densification processes that vary temporally but on independent timescales. Tension fractures dominate the ice sheet surface where ice streaming (i.e., basal sliding) begins, whereas tension fractures dominate both the surface and base of the ice where grounded ice sheets (or ice streams) transition to floating ice shelves. The process that controls the distribution of these fractures is the balance between the strain rate gradient (i.e., the acceleration of the ice) and the ability to accommodate this strain through annealing (which is a function of temperature). Similarly, pervasive and nearly chaotic shear fractures characterize the lateral boundaries of the ice streams over regions that are many times the ice thickness in width. The ice streaming process that controls the position and width of these zones is dominantly stress concentrations at the boundaries of gravity-driven slab flow. Other characteristics of Earth's ice sheets that are rare but possibly relevant include "collapse structures" and ice "blistering". Collapse structures are circular fracture zones several ice thicknesses in width associated with elevated geothermal flux at the base of the ice. Ice "blisters" are zones of vertical uplift, typically meters in width, that are caused by partial melting and refreezing of exposed sub-ice meltwater.

Analogous structural processes on Europa may include vertical density variations in the shallow subsurface caused by the interplay between deposition of sputtering byproducts (e.g., frost) and deposition/erosion associated with gardening/mass-wasting. In addition, the tension-fracture and shear-zone evolution proposed for the hemisphere-scale ridges (with bands) on Europa are a result of tidal flexure and non-synchronous rotation that may have analogs in the on-set, shear-margin and grounding-line evolution of the sub-continental scale Antarctic ice streams. Finally, many of the hypotheses for the formation of pits and spots on Europa parallel those for "collapse" and ice "blister" structures on Earth and it may be possible to extend the hypothesized processes for the slab flow of ice streams to the motion of blocks within larger zones of chaos on Europa.

Compositional State: The compositional state of Earth's ice sheets and ice shelves is dominated by subtle debris and impurity layering. The process driving the layering is surface deposition and vertical advection of material resulting from transient events. The material may be transported atmospherically (e.g., volcanic ash) or through the process of mass wasting (debris fall). The other primary compositional states are represented by units of impure ice found both at the base of and within ice shelves. The process causing these bodies is associated with freezing of sea water either in the low temperature gradient at the ice-water interface (so-called marine-ice units) or in the sharper temperature gradients within cracks that penetrate a substantial portion of the ice shelf. The steepness of the temperature gradient modulates the rate of impurity rejection as the ice freezes. An ice shelf dominated by marine ice formation is the Filchner-Ronne ice shelf of West Antarctica; crack-fill is associated both with tidal flexure at grounding lines and ice berg calving. Often, sub-ice cracks extend into the upper regions of the ice shelf allowing sea water to infiltrate the poorly compacted material and migrate laterally giving horizontally extensive bodies of very impure ice well above any marine ice layer.

Processes on Europa that may be analogous to those described above include the modulation of the deposition of sputtering by-products by transient gardening and mass wasting events resulting in layering of impurities (somewhat analogous to density layering processes). A slow freezing of sub-ice sea water is commonly proposed in association with the infilling of transient melt zones for spot/chaos formation as well as crack infilling for ridge/band formation. Analogous to Earth, a likely implication of these crack infilling hypotheses for Europa would be laterally extensive units of impure ice at the base of any zone of compaction penetrated by the crack.

Conclusion: The ultimate goal of any comparison of processes governing the physical state of Earth's ice sheets and ice shelves with processes operating within Europa's icy shell must be to help define a state space that can be used to evaluate and prioritize experiments for the next mission to Europa. The somewhat naïve associations made here are introduced primarily to initiate discussions on the most effective path to accomplishing this through additional terrestrial investigations.